Food Waste Gasification through Hydrothermal Carbonization Pre-treatment

A. N. Izaharuddin[a], M. C. Paul[a*], S. Theppitak[b], X. Dai[b], Kunio Yoshikawa[b]

[a] Systems, Power & Energy Research Division, School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK
[b]School of Environment and Society, Tokyo Institute Technology, Yokohama 226-8502, Japan
*Manosh.Paul@glasgow.ac.uk; a.binti-izaharuddin.1@research.gla.ac.uk; yoshikawa.k.aa@m.titech.ac.jp

Abstract

Non-recyclable wastes promise great potential for the development of new and robust Waste-to-Energy (WtE) technology. Most of these wastes consist of the vital energy contents which could potentially be converted to various forms of useful energy through advanced thermochemical processes such as gasification, thus helping to reduce landfill of wastes. In gasification technology, syngas (synthesis gas) as the energy source is produced, which mainly includes hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and methane (CH_4) contents. Food waste has a great potential in the energy field as a feedstock and it has the advantage in recovering energy since there is the high energy content help to reduce landfill. The equilibrium model of food waste gasification initially is developed by fixing the value of temperature at 1023K – 1173K with moisture content of 0% - 40% and equivalence ratio of 0.2 – 0.4, by using air as a gasifying agent. Secondly, mass and energy balance equations are solved to calculate the gasification temperature thorugh an iterative procedure. For this research, food waste has been collected and the ultimate and proximate analyses performed, and the data then fed into a gasification equilibrium model to compare the syngas production between non-pre-treatment and hydrothermal carbonisation (HTC) pre-treatment food waste.

Introduction

Food waste refers to appropriate food for a human that discarded whether it is kept after expiry date or not. Usually, these foods are thrown away because it has spoiled and for some other reasons such as oversupply due to markets or the consumer shopping habits [1]. The Waste & Resources Action Programme

(WRAP) and the Department for Environment Food & Rural Affairs reported that a total of 15 million tonnes of food and drink was wasted in the food chain in 2013 which is equivalent to around one-third of the 41 million tonnes of food that is bought annually in the UK [2, 3]. Ko et al. [4] performed an experimental work on food waste gasification by using a fluidized bed with steam. This thermal method converts waste to carbonized solid to produce synthesis gas.

Japanese Government has introduced the efforts of recycling and reducing food waste in an enactment of food waste recycling law in 2000 [5]. Tanaka et al. [6] has identified the basic characteristics of food waste and food ash on steam gasification to design gasifier. Furthermore, this study reported the effects of the highly efficient system in producing hydrogen by adding alkali components in food ash. Additionally, calcium oxide in an ash can absorb CO_2 generated in steam gasification. Ahmed and Gupta [7] has studied both pyrolysis and gasification of food waste, and reported gasification is a preferable process based on the syngas characteristics and char kinetics. Based on previous study, food waste gasification has high potential in the renewable energy field.

Hydrothermal carbonisation (HTC) pre-treatment is a treatment of feedstock (food waste) to convert into char before proceed for gasification. HTC is operated at a mild temperature of up to 524K. Additionally, water is used as a solvent and also as the catalyst [8]. To compare the syngas production of food waste between without pre-treatment and pre-treatment, the experimental work has been done through hydrothermal carbonization (HTC) pre-treatment. An equilibrium model of food waste gasification is developed and verified with other studies. The model is then used to examine the syngas production from gasification of feedstock under both the pre- and non-pre-treatment conditions.

Equilibrium model

Equilibrium model is developed based on the global reaction of gasification as shown below.

$$CxHyOz + wH_2O + mO_2 + 3.76mN_2 \rightarrow x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76mN_2 \qquad (1)$$

In gasification, several reactions occurred, such as the Boudouard reaction, water-gas reaction, water-gas shift reaction and methanation reaction. There are 5 unknowns in this global equation (x_1, x_2, x_3, x_4, and x_5), so need to have 5 equations in a gasification process to determine the value of unknowns which include mass balance and equilibrium constant. The equations include carbon balance, hydrogen balance, oxygen balance, an equilibrium constant for methane formation in equation (2) and an equilibrium constant for water-gas shift reaction in equation (3). Equilibrium constant equations to find k_1 and k_2 are based on the methanation and the water-gas shift reactions, according to Buekens and Schoeters [9], Zainal et al. [10], and Jarungthammachote and Dutta [11].

$$k_1 = \frac{(nCH_4)(n_{total})}{(nH_2)^2} \tag{2}$$

$$k_2 = \frac{(nCO_2)(nH_2)}{(nCO)\ (nH_2O)} \tag{3}$$

The equilibrium model of gasification is initially fixed at 0 – 40% moisture content, 1023-1173K temperature and 0.2 – 0.4 equivalence ratio. After that, mass and energy balance of gasification is calculated to find the gasification temperature by iteration.

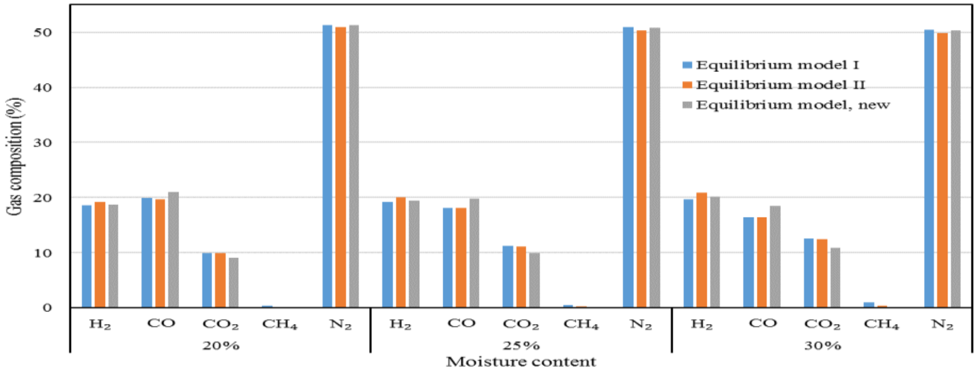

Figure 1. Comparison between Jarungthammachote and Dutta, 2007 [11], equilibrium model at fixed temperature and a new equilibrium model with iteration temperature

Figure 1 shows the comparison of equilibrium model by using solid waste feedstock. From this figure, it shows the gas composition has not so much different between the models, so that the new model can be used for further research, which food waste feedstock. For equilibrium model II, the fixed temperature is 1100K. At MC 20%, the new temperature is 1331.6K, at MC 25% is 1307K and at MC 30% is 1281K. The new CO production is highest between other models, because of temperature increased which effect on the water-gas shift reaction equilibrium constant. For this research, the food waste has been collected to examine the ultimate and proximate analysis, which then run in the equilibrium model that has been developed.

Figure 2. Mixed food waste: as received (left) and after drying (right)

The food waste has been collected and dried for 24 hours as shown in **Figure 2**.

Table 1. Ultimate analysis (dry basis) and proximate analysis of food waste

Ultimate analysis (%)		**Proximate analysis (%)**	
Carbon	58.08	Moisture content	0.96
Hydrogen	8.29	Volatile matter	83.44
Oxygen	30.34	Fixed carbon	14.01
Nitrogen	4.33	Ash	1.59
Sulfur	0.7		

Table 1 shows the ultimate analysis and proximate analysis of dried food waste as a without pre-treatment feedstock sample.

Hydrothermal Carbonization (HTC) pre-treatment

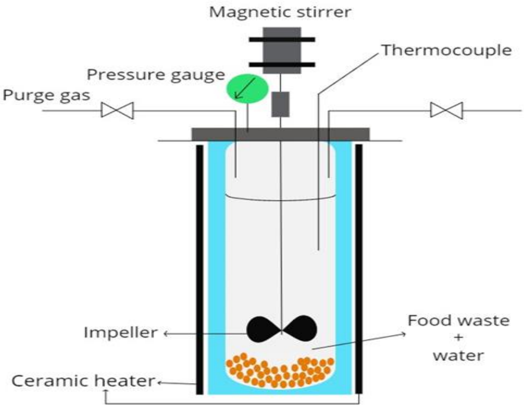

Figure 3. Schematic diagram of hydrothermal autoclave for food waste

Figure 3 shows the schematic of hydrothermal autoclave, which has been used for pre-treatment of food waste. The ratio of food waste to water is 1:5, in which food waste is constant for 40g, while water is constant at 200g. Argon gas is used to purge the gas into hydrothermal autoclave, the water bath is used to recycle the water in the autoclave and the autoclave is heated until the targeted temperature. Once the temperature is reached at the targeted temperature, 30 minutes residence time is started before the cooling process until the temperature reached about 343K. Then, the product is filtered by using vacuum pump, which the solid part is dried for 24 hours at 378K. The operated temperature of food waste hydrothermal at 453K, 473K and 493K.

Table 2. Ultimate and proximate analysis of food waste hydrothermal pre-treatment

Ultimate Analysis (%)				**Proximate Analysis (%)**			
Sample	**I**	**II**	**III**		**I**	**II**	**III**
C	67.29	68.04	70.22	**MC**	0.32	0.70	0.70
H	9.87	9.32	9.45	**VM**	87.20	85.08	83.09
O	18.33	17.43	15.89	**FC**	11.28	13.48	15.73
N	3.66	4.09	3.51	**Ash**	1.20	0.74	0.47
S	0.55	0.74	0.71				

Table 2 shows the ultimate and proximate analysis of food waste for hydrothermal pre-treatment at temperature 453K for sample I, 473K for sample II and 493K for sample III. The fixed carbon increased with increasing temperature.

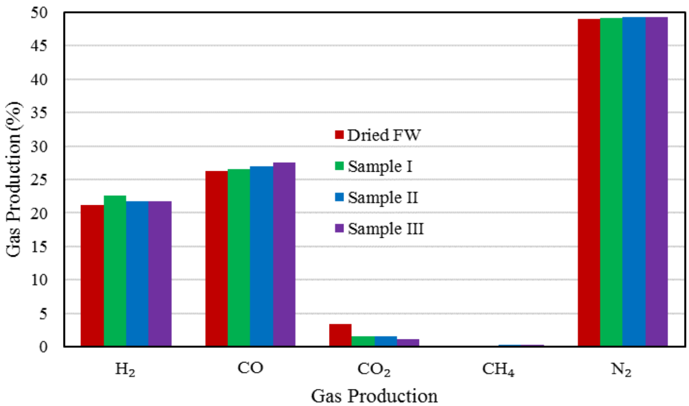

Figure 4: Gas production (%) comparison between dried food waste and hydrothermal conditions sample of food waste

Figure 4 shows the gas production of food waste gasification, which comparison between dried food waste and hydrothermal pre-treatment conditions sample, which sample I is at 463K, sample II at 473K and sample III at 493K. The equivalence ratio for this comparison is constant at 0.34. Through the comparison, H_2 and CO production of hydrothermal conditions shows higher than fried food waste (without pre-treatment). In hydrothermal condition has more carbon than without pre-treatment which could produce more CO through Boudouard reaction and water-gas reaction. Furthermore, H_2 content in pre-treatment sample has higher than without pre-treatment to produce more H_2 which is produced by water-gas shift reaction as well as to reduce CO_2 production.

Conclusion

In conclusion, hydrothermal pre-treatment of food waste is a preferable process to produce more quality char to enhance in food waste gasification. This is shown in ultimate analysis of food waste and the result of gas composition through food waste gasification equilibrium model.

w	Amount of water per kmol biomass
m	Amount of air per kmol biomass
x_1, x_2, x_3, x_4, x_5	The coefficients of product
k_1, k_2	Equilibrium constants
MC	Moisture content
VM	Volatile matter
FC	Fixed carbon

References

[1] FAO, *Food wastage footprint*, in *Impacts on natural resources*. 2013, Food and Agriculture Organization of the United Nations
[2] WRAP, *Estimates of Food and Packaging Waste in the UK Grocery Retail and Hospitality Supply Chains*. 2015, Waste and Resources Action Programme
[3] DEFRA, *Digest of waste and resource statistics-2016 Edition*. 2016, Department for Environment Food and Rural Affairs.
[4] Ko, M.K., et al., *Gasification of food waste with steam in fluidized bed.* Korean Journal of Chemical Engineering, 2001. **18**(6): p. 961-964.
[5] MEGJ, *Sweeping Policy Reform Towards A 'Sound Material- Cycle Society' Starting From Japan and Spreading Over the Entire Globe: The '3R' Loop Connecting Japan With Other Countries* 2006, Ministry of the Environment Government of Japan
[6] Tanaka, M., et al., *Basic characteristics of food waste and food ash on steam gasification.* Industrial & Engineering Chemistry Research, 2008. **47**(7): p. 2414-2419.
[7] Ahmed, I.I. and A.K. Gupta, *Pyrolysis and gasification of food waste: Syngas characteristics and char gasification kinetics.* Applied Energy, 2010. **87**(1): p. 101-108.

[8] Hrncic, M.K., G. Kravanja, and Z. Knez, *Hydrothermal treatment of biomass for energy and chemicals.* Energy, 2016. **116**: p. 1312-1322.

[9] Buekens, A.G. and J.G. Schoeters, *Modelling of Biomass Gasification* in *Fundamentals of Thermochemical Biomass Conversion*, R.P. Overend, T.A. Milne, and L.K. Mudge, Editors. 1985, Elsevier Applied Science Publishers London and New York

[10] Zainal, Z.A., et al., *Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials.* Energy Conversion and Management, 2001. **42**(12): p. 1499-1515.

[11] Jarungthammachote, S. and A. Dutta, *Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier.* Energy, 2007. **32**(9): p. 1660-1669.